USE OF OPTICAL MASERS AS TRANSDUCERS FOR PENDULUM AND STRAIN SEISMOGRAPHS

Leonard E. Alsop

Lamont Geological Observatory
Columbia University
Palisades, New York

Grant No. AF-AFOSR 283-63

Project-Task 8652

Final Report

Period Covered: 5 April 1963 - 31 October 1965

1 November 1965

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WASHINGTON, D. C.

WORK SPONSORED BY ADVANCED RESEARCH PROJECTS AGENCY

PROJECT VELA-UNIFORM

ARPA Order No. 292-63 - Amendment 5

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ABSTRACT

During the period of this grant, two one-meter infrared optical masers were operated in a manner such that horizontal strains would be detected. The first results have been encouraging and suggest that optical maser strain gauges will be able to compete with the much longer conventional strain gauges. An optical maser transducer for a seismograph has been built but tests have been delayed pending the completion of a temperature-control system. A special short-period seismograph to be used with this transducer was constructed. This work on optical masers stimulated the use of optical masers for optical recording and interferometric calibration by other workers at Lamont.

I. INTRODUCTION

The initial tasks set for this grant were the design and construction of two stable infrared masers; the design and construction of a short-period vertical pendulum seismograph suitable for use with an optical maser transducer; the mating of these two elements so that the combined optical maser transducer seismograph could be placed in operation; and the operation of a horizontal strain seismograph formed from an optical maser. The following things were accomplished during the period of the grant. Several infrared and red masers have been constructed and tested. Two infrared masers have been constructed and tested for stability in the transducer frame for the seismometer, but, as yet, no temperature stabilization has been attempted, so the device does not, at present, have sufficient long-term stability to be used as a transducer for a seismograph. It is hoped to accomplish this in the near future. The short-period vertical seismograph has been constructed, and the initial testing with a displacement transducer has been completed. Two infrared optical masers have been operated in a configuration suitable for the detection of horizontal strain in the deep New Jersey Zinc Company mine in Ogdensburg, N. J. The initial results indicate that it will be possible to do at least as well with two one-meter-long masers as with present strain gauges with lengths of 50 meters or greater. Such a development should be of great importance to Project VELA-UNIFORM, since it would be much easier to operate such strain gauges together with pendulum seismometers, as has been suggested by Romney, to improve the detection capability. Another interesting study in progress is the use of lasers as light sources to obtain magnification over that currently obtainable for conventional instruments by the use of large optical lever arms. Also, the group at Lamont working with the conventional strain gauges was stimulated by this work into constructing a laser interferometer for calibration purposes, which has proven to be very successful. These various topics will be discussed in more detail in the body of this report. For the convenience of the reader, a summary of the applicable theory necessary to understand the uses of optical masers is included in the next section.

II. THEORY

The word "maser" is an acronym for Microwave Amplification by Stimulated Emission of Radiation. In order for stimulated emission to take place, there must be more atomic systems in a high energy state than in some lower energy state. Under conditions of thermal equilibrium, such a situation never occurs, and electromagnetic radiation is absorbed rather than amplified. Various schemes have been used to upset the thermal equilibrium between energy states with an energy difference corresponding to a microwave frequency. The original ammonia maser removed ammonia molecules in the lower state of the 3, 3 inversion transition by electrostatic focusing. In another type, the population imbalance between spin energy states of paramagnetic crystals used as maser amplifiers is obtained by equalization of the populations of the lower state and a third state with energy greater than that of the second state. Other methods are also possible. In most microwave masers, the active maser material is placed in a microwave cavity resonant with the frequency of stimulated emission, in order to achieve a large electromagnetic field energy at this frequency.

The extension of maser techniques into the infrared and optical regions was suggested by Schawlow and Townes. Different techniques are required in these regions than in the microwave region. In the following discussion, we will consider only the gaseous infrared maser proposed by Schawlow and Townes, and modified and perfected by Javan et al. The various solid-state optical masers are not suitabl for these types of transducers.

It is impractical to build standard resonant cavities at infrared frequencies. Therefore, multimode cavities are used. The cavity consists essentially of two reflecting plates separated by a distance, D. The plates may be inside or outside of a tube containing the gas. Losses of energy are permitted through the sides of the tube. The modes which exist have been studied by Fox and Li. They found that the normal modes with the least loss for circular plates were the various multiples of the TEMoo mode, which show no angular variation and which confine the energy to the center of the plates. The frequency difference between these modes satisfies the Fabry-Perot condition

$$\delta\nu = c/2D \tag{1}$$

where C is the velocity of light and D is the distance between the plates. Thus, for a D of one meter, the frequency interval between modes is 150 mc. The line widths of transitions in the infrared range are usually much greater than this, so several cavity modes will lie within the resonance.

The mechanism used by Javan to obtain the desired population imbalance is as follows. He created a discharge in a gas containing 0.1 mm Hg of Ne and 1 mm Hg of He. The helium is excited by bombardment from the electrons in the discharge. The 2^3s state of helium is metastable. The excitation energy of the helium in this state can be transferred to the neon by collision with a neon atom in the ground state. However, because of the resonant nature of this process, those neon levels with energies near that of the metastable state are preferentially excited. Thus the 2s states of Ne are excited while the lower-lying 2p states are not. Therefore, maser action can occur between these levels. The power efficiency is very low. The actual power supplied by the exciting transmitter is about 50 watts. The maser oscillation power output is about 1.5 milliwatts.

Maser oscillators are characterized by extremely monochromatic radiation. The slightly preferential stimulated emission at the peak of the resonance causes the power in the cavity to build up appreciably at this frequency because the energy produced by stimulated emission is much larger than that due to spontaneous emission or thermal noise. The result is a narrowing of the bandwidth of the emitted frequency. This effect is quite large. Theoretical considerations yield the result that at an infrared frequency of 1.5×10^{14} cps, the bandwidth is less than 1 cps. This width will be broadened by instabilities of the optical cavity due to mechanical noise and thermal expansion.

Expression (1) indicates how an optical maser may be used as a transducer. The oscillation frequency ν_{osc} will be some integral multiple m of $\delta\nu$.

$$\nu_{osc} = m\,\delta\nu = mc/2D \qquad (2)$$

Differentiating (2) yields

$$\frac{d\nu}{\nu_{osc}} = -\frac{dD}{D} \qquad (3)$$

The fractional change in the oscillation frequency is equal to the fractional change in the distance between the two plates, but directed oppositely. Now $-\frac{d\nu}{\nu_{osc}}$ should be measurable to a part in 10^{13} to 10^{14}. This means that with a one-meter maser a shift of 10^{-4} millimicrons should be detectable. Presently existing seismograph displacement transducers can measure a shift of only about 10^{-1} millimicrons.

The actual method of measuring the frequency shift is as follows: Two masers are required. One provides a reference signal, the second acts as the transducer. The infrared radiation from the two masers is shone on the photosensitive surface of a photomultiplier tube, which is a square law detector. As a result, the beat frequency between the two masers is obtained. Variations in the plate distance of the second maser cause a proportional variation in the beat frequency.

It is possible to obtain beat frequencies from 0 to 500 mc with existing photo-multipliers. This places an upper limit on the displacement which the maser can measure. For masers with D greater than about 20 cm, the value of $\delta\nu$ from (1) places a lower upper-limit than this on the displacement, for the frequency can be shifted by only about one-third the distance between cavity modes if the oscillation is to be confined to one cavity mode. These considerations yield a dynamic range for the maser of about 10^7 or 140 db.

III. OPTICAL MASER SEISMOGRAPH TRANSDUCER

The optical maser transducer frame plus two Brewster angle tubes is shown in Figure 1. The frame is constructed of aluminum. The one and one-half inch thick plates which support the mirrors are separated exactly a distance of fifty centimeters by three one and one-half inch diameter posts. Supports for the Brewster angle tubes may also be seen. At present, all four mirrors are fixed. When the maser is mated with the vertical seismograph, the bottom mirror at the center will be supported on the mass of the seismograph, and its motion will be monitored by observing the change in frequency. At the top of the frame may be seen a block which holds three plane mirrors at just the proper angles for bringing the two maser beams into parallel coincidence on the photomultiplier surface.

The optical masers have been operated in this frame and the stability of the beat note has been determined to be several parts in 10^{10} over short periods of time. This is of the order that Javan has estimated for optical masers with Brewster windows because vibrations of the windows cause significant changes in the optical path length of the Fabry-Perot cavity. The long-term stability is worse by several orders of magnitude. This may be attributed solely to thermal expansion of the rods since there is, as yet, no temperature contol of the device nor its surroundings. The effect of vibrations of the windows upon the short-term stability may be eliminated by using windows coated with anti-reflectant coatings and placed at an angle of ninety degrees to the axis of the gas tube rather than at the Brewster angle. Then the effect of small changes of the angle of the windows is negligible.

The contemplated temperature control requires the optical masers to be in near-vacuum conditions and, therefore, an attempt was made to operate the tubes in an atmosphere of the correct pressure of helium and neon without windows. The optical masers operated in this configuration for approximately three hours and then ceased. Inspection showed that the coatings of two of the mirrors had been damaged, presumably by electron bombardment. We discussed this matter with Perkin-Elmer and were informed that a similar effect has been observed in a few cases where DC internal mirror operation has been attempted. Other coatings, however, have resisted the bombardment, but the state of the art has not yet been reached where they can guarantee that any particular coating will be durable. Therefore, this type of operation is not feasible at this time, and closed tubes must be used.

IV. SEISMOMETER FOR USE WITH OPTICAL MASER TRANSDUCER

The design parameters of the vertical seismometer to be used with an optical maser transducer, as selected at the initiation of this project, were:

1. Inertial mass: 8 Kg
2. Free period of suspension: 0.5 sec
3. Damping coefficient: 6 times critical

These parameters were arrived at on the basis of:

a) required frequency response characteristic for broadband seismic observation with a displacement-type transducer, and:

b) maximum signal capability of the proposed optical maser transducer ($\pm$ 0.1 micron).

Given these parameters, it is important to neutralize as much as possible the influences of temperature, pressure, and external magnetic field variations on the relative mass-to-frame position.

The adopted design uses a set of three centrally-loaded, diamond shaped leaf springs. These springs, made from a nickel-iron alloy (Ni-Span C) having a controllable temperature coefficient of the elastic modulus, are formed to a uniform radius (R = 6.140 inches), and heat-treated to achieve the required thermal characteristics.

Figure 2 shows the top of the seismometer assembly. The springs, directly attached to a Y-shaped structure supporting one of the cavity mirrors, are visible. The damping coil is attached directly underneath.

The damping coil constitutes the main part of the seismic mass. In combination with the magnetic circuit, the electrodynamic constant, as measured, is 2015 Newton/Amp. The total coil resistance is 3985 ohms.

The magnetic circuit, built up as two, opposing, conventional "voice-coil" circuits, provides a completely enclosed and very uniform coil field. The total magnet volume (ALNICO V-7) is 1000 cm^3.

A capacitor plate displacement transducer, with a sensitivity of 625 mV/micron, and a minimum detectable signal of less than 10 millimicrons (5 cps bandwidth), has been built in, with its associated transistor circuitry.

The general layout of the seismometer minimizes the number of elements and the total lengths of material joining the maser frame to the inertial reference.

By adjusting the temperature coefficient of the spring, to compensate for any remaining thermal expansion, and by controlling the temperature environment, it is expected that instrument deviations can be made independent of outside temperature variations.

It has been determined that the "noise" output of the seismometer is below the minimum detectable level of 10 millimicrons. This limit, imposed by the noise level of the present transducer, can be lowered by refining this circuit.

As is, the seismometer mass-to-frame motion is well within the maximum signal capability of the laser transducer.

Figure 3 is a seismic record obtained recently from the capacitor plate transducer. The recording setup included a filter-amplifier, peaked at 20 seconds. The total system magnification on this record is 10000 from .05 seconds to 3 seconds, down to 1500 at 20 seconds, and dropping to 12 at 100 seconds.

V. OPTICAL MASER STRAIN GAUGE

Since optical masers measure $\delta D/D$, they are natural strain gauges. Therefore, experiments were initiated on a seismic test pier in the Seismology Building using optical masers as strain seismographs. The configuration chosen is quite simple. Two mirror-holding stands each are mounted one meter apart and at right angles. One half silvered mirror only is required to bring the two beams into parallel coincidence on a photo-multiplier tube. For convenience in setting up at remote locations plus a twofold increase in sensitivity, these experiments were conducted with visible red (6328 Å) masers.

The stability for this device showed the same results as for the infrared masers mounted in the seismometer transducer frame. A short-term stability of several parts in 10^{10} was observed, probably limited by cultural noise. The observed long-term stability was poorer, again because the room in which the experiment was done is subject to large thermal variations.

An infrared maser strain gauge was recently moved to the 1850-foot level of the New Jersey Zinc Company mine at Ogdensburg, N.J., where the Lamont quartz tube strain gauges are already in operation. A recording system composed primarily of a counter and a digital-to-analog converter was also brought to the mine to record the output of the strain gauge. The initial results have been very encouraging. Samples of up to 36 hours of continuous output from the optical maser strain gauge have been recorded. The long-term stability is much better in the mine, as had been expected. Drifts of approximately one or two tidal amplitudes per day are now being obtained, but the instruments have not been given enough time to settle down. The initial short-term noise was of the order of several parts in 10^8. This has now been reduced to about a part in 10^9, and efforts are continuing to obtain further reductions. The present long-term drift makes it difficult to see tides, but a record has been obtained which seems to show tides of about the expected magnitude.

On the basis of the tests at Lamont and Ogdensburg, it seems safe to say that one-meter long, optical maser strain gauges will be able to detect strains of several parts in 10^{11}, which is comparable to the sensitivities of present 60m quartz tube strain gauges. It is interesting to note that the present noise levels and drift rates are comparable to those first obtained when the quartz tube strain gauges were being installed. It is still too early to state whether the proposed goal of one part in 10^{12}, comparable at short periods to a Benioff with a gain of half-a-million, can definitely be achieved.

Romney, in an article in the December 1964 issue of the Bulletin of the Seismological Society of America, has discussed the advantages to be obtained in detecting P waves by using a combination of pendulum and strain instruments. The size of present strain gauges makes this technique difficult to apply. The optical maser strain gauges, with their smaller size and, perhaps, better sensitivity, would be ideal for this purpose.

VI. OPTICAL MAGNIFICATION WITH MASER LIGHT SOURCES

Because optical masers produce beams with extremely narrow beam widths and of great intensity, they are ideal sources of light to be sent over large distances. A simple application is their use in connection with long optical lever arms in order to obtain signal amplification. Records have been obtained from one of the strain meters at Ogdensburg using this principle. The strain meter tube was allowed to push against a mechanical linkage to which was attached a mirror. The mechanical amplification was 20 to 1. Further amplification was obtained by shining light on the mirror from an optical maser located ninety feet away from the mirror and then back to a photographic recorder located near the maser. The records obtained are comparable to conventional records obtained with electronic amplification at the same time.

This first experiment was quite crude, in that very poor quality optical equipment was used. Even so, the optical magnification was a factor of thirty better than normal. With improved optics and by using multiple reflections, much greater improvements can be expected.

VII. MASER INTERFEROMETER CALIBRATION SYSTEM

Measurement of tidal strain on extensometers requires accurate amplitude calibration. This has always posed a problem since the maximum tidal strain as observed on the 200 ft. N29°30'E extensometer at Ogdensburg, N. J., is 4.5×10^{-8} or 3 microns. Thus a reliable calibration system should provide repeatable measurements for induced tube displacements of 1 - 3 μ.

For the past few years, the Lamont tidal strain calibration system has consisted of two parts:

1. a remote-controlled electromagnetic driving unit excited by a low-frequency oscillator;
2. a high magnification optical system comprised of a 600-power microscope and cross-hairs for direct viewing of tube displacement.

The accuracy of this system at first was thought to be ± 5 percent or $\pm 0.15\,\mu$. However, recently, by employing a Michelson interferometer with a gaseous maser as a light source, the accuracy of the microscope system has been shown to be as bad as ± 30-50 percent.

The highly monochromatic visible light emitted by a Helium-Neon gaseous maser allowed a convenient and accurate interferometer to be set up for calibration of the extensometers. The actual system used consisted of the following:

1. the electromagnetic driving unit mentioned previously which expanded and contracted the tube every 10 sec;
2. a maser interferometer comprised of one adjustable mirror and beam splitter mounted on a quartz standard approximately two feet in length. Another mirror was mounted on the extensometer close to the electromagnetic driving unit. After an easy alignment, an interference pattern was projected to a convenient distance for observations. The extensometer tube

was then driven and the resultant fringe shift observed visually during an expansion and contraction.

With comparative ease, a 1/4 fringe shift could be observed. In this case, 1/4 fringe = 1/8 λ, where λ = 0.6328 microns, giving an approximate $\pm 0.1 \mu$ or ± 5 percent accuracy.

In the future, more elaborate methods could be employed to observe the fringe shift, but this recent experiment has shown that the accuracy of the maser calibration system is 5 - 10 times better than the microscope system.

VIII. CONCLUSIONS

The schedule of accomplishments outlined in the initial proposal for this grant proved to be overly optimistic. An initial delay of six months was caused by a two-month difference between the initial date of the contract and the time at which the funds were made available plus four months before all of the initial equipment was available. Delivery delays, particularly for optical parts, have been a constant source of annoyance to us and to others working in the rapidly expanding field of maser research. Another cause of delay was the very detailed and accurate machining required for the seismometer and the optical maser mixing head on the seismometer transducer frame. A further complication arose when moisture in the mine destroyed the soft optical coatings on the mirrors. These have been replaced by recently-developed hard coatings.

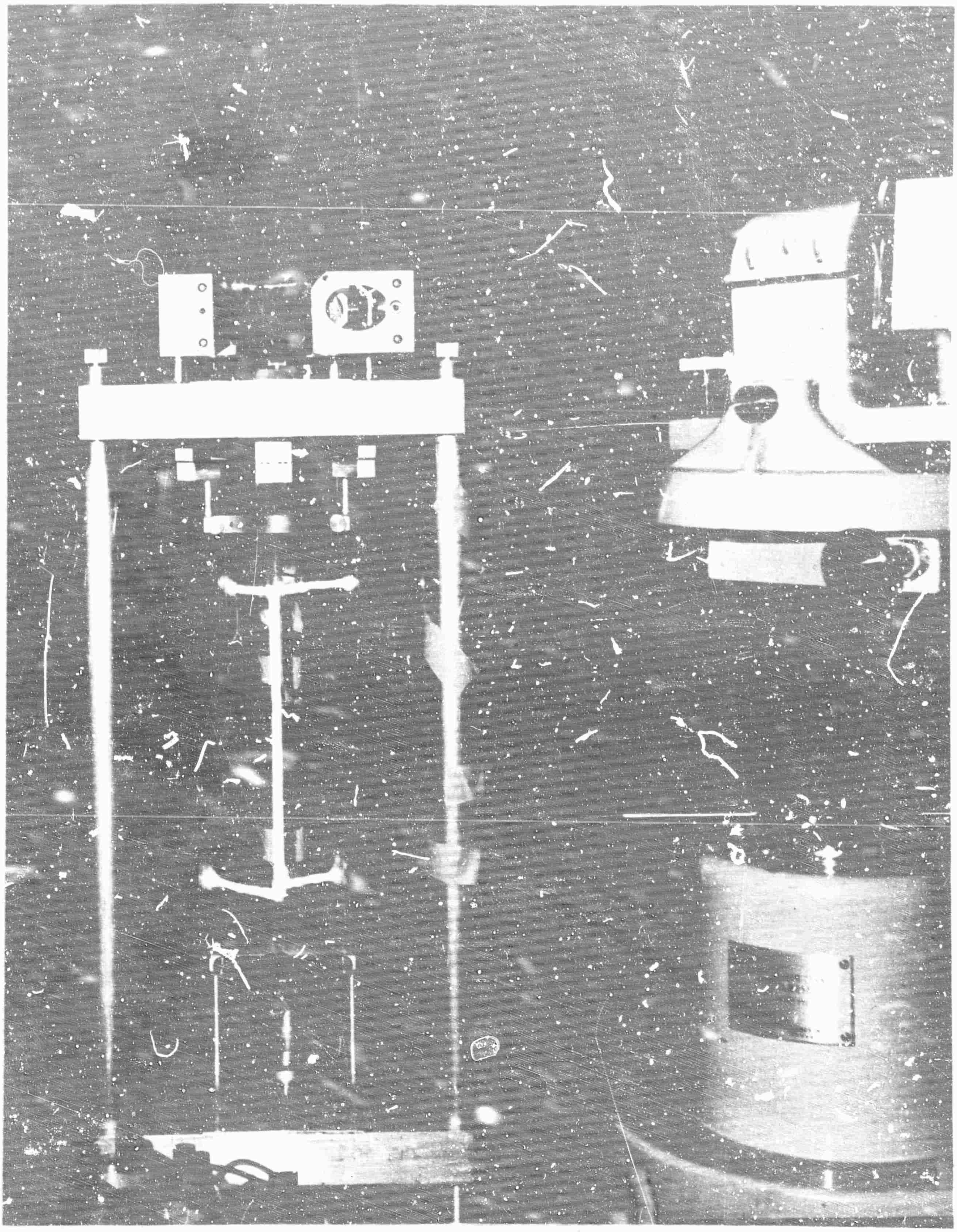
The strain seismometer is now at the stage of being debugged. The pendulum seismometer is ready. The mating of the two elements of the optical maser seismograph is in process, and it, too, will then be at the stage of being debugged. Therefore, it seems reasonable to exoect that the strain seismometer could be placed in operation within eight months and the vertical seismometer within one year.

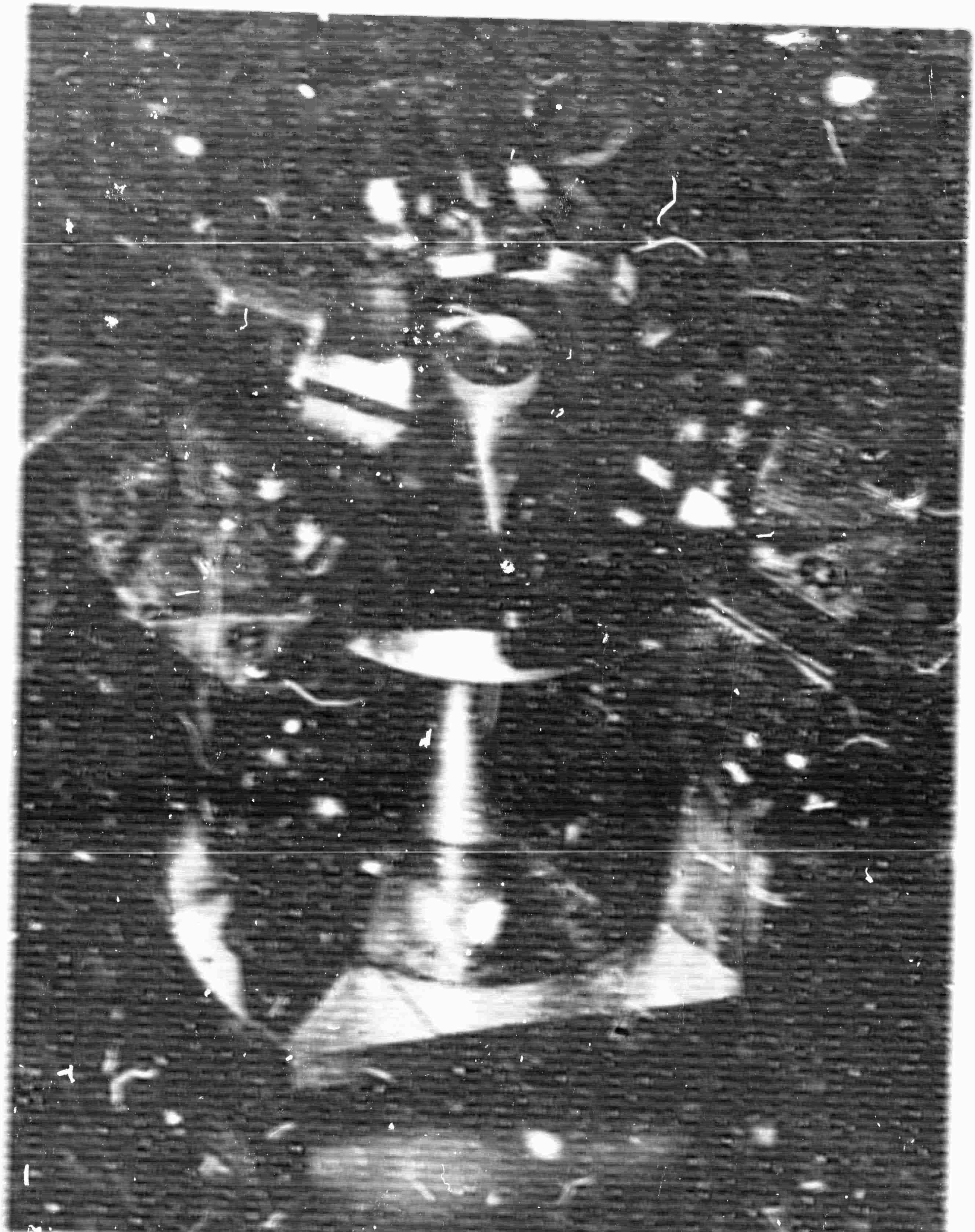
PUBLICATIONS

Hade, Jr., G., M. Conner, and J. T. Kuo (in preparation), "A remote-control calibration system for strainmeters."

FIGURE CAPTIONS

Figure 1	View of Optical Maser Seismograph Transducer
Figure 2	View of Vertical Seismometer to be used with Optical Maser Seismograph Transducer
Figure 3	Sample Record obtained from Vertical Seismometer





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